On the Shape of the Carbon Mira Star S Cep

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ABSTRACT

In this paper we report observations of S Cep, a carbon-rich Mira variable star, that indicate clear departures of the disk brightness distribution from circular symmetry. The simplest interpretation is that the photosphere shows elliptical symmetry with an axial ratio $a/b \approx$ 1.17 and with the major axis lying at a position angle of about 21°. Similar observations of the oxygen-rich luminosity class III star SS Cep do not show such an effect. S Cep is the first carbon star for which asymmetry observations of the photosphere have been reported although it is not the first star in which asymmetries have been seen. We emphasize that all asymmetric red giant stars so far observed are among the most extended stars known while smaller stars, perhaps typified by SS Cep, do not appear to show departures from circular symmetry. The observed intrinsic polarization for S Cep has an electric vector that is nearly perpendicular to the major axis of the ellipse and with an amount that may be consistent with its production by scattering in the asymmetric photosphere

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I. INTRODUCTION

Mapping the brightness distribution over the surface of the largest stars is an important step toward understanding structural and atmospheric stellar dynamics. A non-uniform brightness distribution might indicate a globally-distorted photosphere or the presence of granular structure on the surface. The largest stars, other than the Sun, have angular diameters of about 50 milliarcsec (mas), which is the diffraction limit (λ/D) for a telescope with a diameter D = 2 m at a wavelength λ = 0.5 μm. Thus, only marginal resolution is possible for the largest stars, except with the largest optical telescopes. Karovska *et al.* (1991) used speckle interferometric techniques at 4-m telescopes to deduce that the photosphere of Mira had a roughly elliptical shape whose ellipticity appeared to decrease with increasing wavelength over the range from 533 nm to 850 nm. A close inspection of the data indicate that the apparent decrease of the departure from circular symmetry could simply be a problem of the growing diffraction limit for a 4-m telescope and, hence, the decrease in resolution. Haniff *et al.* (1992) used an aperture masking technique on the Hale 5-m telescope and obtained results for Mira that were consistent with those of Karovska *et al.* (1991). Mira was also observed with the Mark III interferometer, at about the same epoch, by Quirrenbach *et al.* (1992), who showed that the asymmetry still existed at 800 nm. In his PhD thesis, Peter Tuthill (Tuthill 1994) reported aperture masking observations, made at a 4-m telescope, of 5 Mira variables, including Mira itself, that indicated departures from circular symmetry. In this work, closure phase information allowed Tuthill to conclude that the asymmetries arose from non-centro-symmetric brightness distributions such as spots on the surface. Tuthill's observations represent the most complete data set although he notes that the time series is inadequate to distinguish among a variety of models.

The introduction of large-baseline interferometers into routine use at optical wavelengths overcomes the difficulties imposed by diffraction, although full imaging capabilities are still in a rudimentary stage at present. For example, a two-telescope interferometer with a baseline of 35 m has a λ/D diffraction limit of 13 mas at 2.2 μm. However, no phase information is directly available from the observations, limiting the interpretability of the data. The purpose of this paper is to report observations made at IOTA (the Infrared Optical Telescope Array) that search for departures from circular symmetry in S Cep, a carbon-rich Mira variable, and SS Cep, an oxygen-rich semi-regular variable classified M5III (Keenan 1942); these are the first such observations of a carbon-rich star. We demonstrate that S Cep shows an asymmetry corresponding to a major axis/minor axis ratio of about 1.2, somewhat smaller than that reported by Karovska *et al.* (1991) for Mira at 533 nm. On the other hand, the observations of SS Cep are consistent with a circularly-symmetric brightness distribution for the stellar surface. We discuss the differences between the most extended evolved stars and the normal giants and spend some time considering the effects of a rotationally distorted star, for the case of S Cep.

II. OBSERVATIONS

The data reported here were taken in October 1996 using the InSb detectors and 2.2μm filter with IOTA in a configuration previously described by Carleton *et al.* 1994 and Dyck *et al.*

1995. The two telescopes were positioned at the xx m (NE arm) and the yy m (SW arm) of the interferometer. The choice of two stars at a high declination allowed us to observe much of the night, with the apparent position angle (PA) and telescope separation (that is, the projected baseline, B_P) changing as the source is tracked. These changes result in sampling at different spatial frequencies and azimuths projected onto the source. Thus, departures from spherical symmetry will be seen as discrepancies between the observations and the visibility expected for a circularly-symmetric model, plotted as functions of PA and B_P.

As is usually the case, observations of the sources were interspersed with observations of calibrators, point-like stars that are sufficiently small that any intrinsic asymmetry will be masked by the interferometer angular resolution. The calibrators are chosen to lie in the same part of the sky as the source and observations of them are made immediately before and after the source. In the reductions, we divide the raw fringe visibility for a particular source observation by the average raw fringe visibility for the calibrators observed before and after (in time). This division removes the combined response of the instrument and atmosphere and yields the calibrated fringe visibility, V. However, we expect that the observed visibility effects will be small and it is better to have a stable interferometer than one for which the response fluctuates wildly during the night or from night to night. To illustrate this stability, we have shown in Figure 1 the raw calibrator visibilities for the calibrator used for S Cep as a plot of observed fringe visibility versus B_P. The particular calibrator shown (IRC+80052) has an angular diameter of 3.4 mas, leading to an expected visibility of about 96% at 2.2 µm for the range of baselines used during the observations. Note that the actual observed visibilities are about 42%, so that the interferometer response is approximately 44%. We have shown, as a dashed line in the figure, the expected variation of the calibrator visibility as a function of projected baseline and scaled by the interferometer response. It is clear that the calibrator observations follow this trend well, with a peak-to-peak scatter of about 12%. This dispersion represents the maximum excursion of the interferometer-plus-atmosphere response during the sequence of observations of S Cep.

The calibrated visibilities for S Cep and SS Cep are listed in Table 1 and Table 2, respectively. We have given the date (as year-month-day), universal time, projected baseline, position angle, calibrated visibility and error in the visibility. One may see that, for S Cep, the PA varies by more than 45° during which time B_P changes by 1.25 m (about 4.5%). For SS Cep, the corresponding changes are more than 115° and 7.7 m (33%). Our ability to interpret the data will be sensitive to the range of change of both quantities.

II.1. S Cep

In Figure 2a and 2b we have plotted the calibrated visibility observations of S Cep versus position angle and projected baseline, respectively. One notices immediately that there is a problem with a simple interpretation of the visibility in terms of a circularly symmetric source by the behavior of V versus B_P *because the visibility increases with increasing baseline.* For any circularly-symmetric geometry, the visibility must decrease with increasing baseline (see, for example, Fomalont & Wright 1974). This is illustrated in the figure by model visibilities for a

uniformly-bright circular disk and for a circularly-symmetric Gaussian brightness distribution. Both of these model visibilities decrease with increasing baseline, opposite to the observed effect. Notice also that there is a general decline of the model V versus PA as well. This results from the fact that there is a relationship between PA and B_P, such that (for this case) the projected baseline decreases with increasing position angle. The model visibilities, therefore, change in the opposite sense to the observations for PA as well as for B_P. Note also that there is very little perceptible difference between the circularly-symmetric Gaussian and the uniformly-bright circular disk models, over this range of projected baseline. Thus, for the purpose of further discussion, we adopt the Gaussian model since it is somewhat easier to use computationally.

As we noted earlier, the lack of Fourier phase information in the observations precludes the development of a particularly sophisticated image model. We chose, instead, the simplest *2D* brightness distribution, namely, the elliptical Gaussian, characterized by different full widths at half maxima (*FWHM*) in two orthogonal directions and by the *PA* of the major axis on the sky. The measured visibilities have been fitted by a Gaussian *FWHM* in each *PA* observed; these are shown plotted in Figure 3 in a field size 10 mas on a side and where north is to the right and east is up. The *FWHM* so derived were then fitted by an ellipse, the parameters for which are $FWHM_a = 10.1$ mas, $FWHM_b = 8.6$ mas and $PA_a = 21.5^{\circ}$, where $FWHM_a =$ full width at half maximum for the major axis, a, $FWHM_b =$ full width at half maximum for the minor axis, b, and $PA_a =$ position angle of the major axis measured from north through east. This model is shown for comparison in Figure 3 and appears to fit the observations reasonably well. Thus, the result of this simple analysis is that the visibility observations for S Cep may be interpreted as though the star has an elliptical shape with an axial ratio $a/b \approx 1.17$.

We have computed the expected variation of the model visibility with B_P and PA and shown the results in Figure 4a and 4b, compared to the observations. Note now that the model visibilities behave correctly with respect to the observations and fit the observations well. One further point of interest is seen in the plot of V versus B_P: In the range of baselines between 28.0 and 28.2 m there is a cluster of observations. A close inspection of the figure shows that the model visibilities hook back at this point, leading to the higher density of points. This occurs because of the functional relationship between the interferometer's PA and B_P and the orientation of the star's major axis with respect to the interferometer.

II.b. SS Cep

By contrast, no such behavior is seen for SS Cep. The observed data are shown plotted in Figure 5a and 5b, compared to a circularly-symmetric Gaussian. While the data do not fit the model perfectly, they do not show the same systematic departures previously discussed for S Cep. It is possible that the differences between the observations and the simple model do indicate some level of surface structure although they do not appear to indicate departures from a simple circular shape. SS Cep is more difficult to measure because it is not as resolved as S Cep and higher signal-to-noise ratio data would be needed to infer the presence of image sturcture. For comparison with S Cep, we interpret SS Cep as a circularly-symmetric source.

III. DISCUSSION

We have found that the carbon-rich Mira variable S Cep shows evidence for departure from circular symmetry while the oxygen-rich giant star SS Cep does not. S Cep represents the first carbon star for which asymmetry observations have been made but it is not the first star to show such geometry. We emphasize here that all other stars with reported asymmetries are either Mira variables or supergiant stars (Tuthill 1994). We are not aware of any observations of luminosity class III stars that indicate convincing departure from circularly-symmetric brightness distributions. Previous work indicates that the radii of the Mira and supergiant stars are hundreds of $R_\odot$ (Haniff, Scholz & Tuthill 1995, van Belle et al. 1996). In particular, if we take the distance for S Cep, $d \approx 390$ pc, determined by Claussen *et al.* (1987) from statistical arguments, and combine it with a uniform-disk angular diameter of $\theta_{UD} \approx 14$ mas obtained in the present work, we obtain a photospheric radius $R_* \approx 590\ R_\odot$. On the other hand, the radii of the cooler luminosity class III stars are tens of $R_\odot$ (Dyck *et al.* 1996); in fact, an M5III star would be expected to have a radius of about 100 $R_\odot$. ***Thus, the observed departures from circular symmetry appear to be associated with the most physically extended stars.*** Further observations of a wide variety of stars will help to clarify this apparent effect.

Even without image Fourier phase information we may expect to be able to constrain possible models for the brightness asymmetries by continuing observations of S Cep, specifically, and of other stars in general. A detailed time sequence of observations such as those reported here will clearly indicate gross changes of shape and orientation as functions of time. With these data we may be able to comment upon the applicability of non-radial pulsations or rotationally-distorted photospheres as possible sources of asymmetry. In particular, it would be interesting to observe the carbon-rich Mira V Hya that has a reported direction for an asymmetry that has been interpreted to arise from a rapidly-rotating star (Barnbaum, Morris & Kahane 1995).

We may speculate a bit about rotational distortion of the photosphere of a star. The centripetal acceleration at the equator, resulting from the rotation, offsets the effect of gravitational acceleration owing to the mass of the star. If we take, to first order, that the ratio a/b is equal to the ratio $g_{pole}/g_{equator}$, where g = surface gravity, then we may derive the equatorial rotational velocity, assuming we view the star at an inclination angle i. Under these conditions,

$$v\ \sin\ i \approx \sqrt{\left(1 - \frac{R_{pole}}{R_{equator}}\right) \frac{G\,M_*}{R_*}}\ ,$$

we have that

where R = observed stellar radius at the pole or equator (depending upon the subscript), M_* = stellar mass and R_* = average stellar radius. From our measurements we obtain the values of R. Claussen *et al.* (1987) estimate that the progenitors for carbon stars have masses in the range

1.2-1.6 $M_\odot$; we take the mean of these values. Putting these into the last equation yields a rotational velocity $v \sin i \approx 8$ km/sec; this would lead to an observable line broadening $\Delta v \approx 16$ km/sec. Barnbaum, Morris & Kahane (1995) mention S Cep specifically in their study of rotational broadening of spectral lines and comment that it is one of two carbon stars (other than V Hya) that have noticeably broad lines. These lines could, in the authors' opinions, arise from the weak line doubling noted in the spectrum. (What are the actual line widths? This number should be discussed here........)

However, we may take the same line of reasoning that these authors do and investigate the effects of a beat period in the light curve of S Cep, arising from an interaction between pulsation and rotation. The breakup velocity of S Cep, from the radius determined in this paper, and an assumed mass of $M \approx 1.4\, M_\odot$, is $v \approx (GM_*/R)^{1/2} \approx 21$ km/s. Hence, the minimum rotation period for the star would be 1400^d, indicating a maximum beat period of 750^d. From a Fourier analysis of the visible wavelength light curve obtained from the AAVSO and AFOEV (Mattei 1997, Schweitzer 1997), we find that there only marginal evidence for a second period, of duration $P \approx 4010^d$. If this is interpreted as a beat period between rotation and pulsation then we infer a rotation period $P_{rot} \approx 550^d$, which would indicate a rotational velocity of 54 km/s, well past breakup velocity. Hence, we regard the second period as spurious; this is consistent with a similar analysis we performed upon V Hya, which has convincing evidence for its second period of 6300^d.

There are also measures of the linear polarization of S Cep in the literature. Zappala (1967) observed the star for about 150 days and found average amounts and position angles $P \approx 1.2\%$ and $\theta \approx 130^o$, respectively. The amount fluctuated during the observations but the position angle remained nearly constant. Zappala argued that the star was intrinsically polarized owing to its high galactic latitude and to the fluctuations in the amount of polarization. More recently Bel *et al.* (1993) observed the region surrounding S Cep, in a study of interstellar polarization. Their measured amount was 1.0%, while the position angle was $\theta \approx 114^o$, in the equatorial system; the amount of polarization is similar to the mean measured by Zappala although the position angle appears to have decreased by about 15° during the intervening 25 years or so. S Cep is projected onto the Cepheus molecular cloud defined by Grenier *et al.* (1989) and centered at about $l = 110^o$ and $b = 17^o$. We inspected the polarization for stars lying in the galactic coordinate range $110^o \leq l \leq 115^o$, $15^o \leq b \leq 20^o$ that were reported by Bel *et al.* The mean amount and position angle (obtained by averaging Stokes' parameters) were found to be $P \approx 0.15\%$ and $\theta \approx 87^o$, respectively. If we assume that this small amount of interstellar polarization is also added to the observed polarization of S Cep then we may correct the recent observations by subtracting the interstellar Stokes' parameters from the stellar Stokes' parameters. This results in an assumed *corrected stellar intrinsic polarization* for S Cep of $P \approx 1.2\%$ and $\theta \approx 117^o$. Recalling that the position angle for the major axis of the ellipse describing the photosphere of S Cep is 21°, we find that the position angle for the polarization electric vector is 96° away from the major axis of the ellipse. This is temptingly close to the 90° expected if the observed intrinsic polarization of S Cep were produced by scattering in a flattened photosphere. Collins

and Buerger (1974) have noted that polarizations of order 1% *may* be produced in "late-type supergiants that have been severely distorted either by rotation, pulsation, or large magnetic fields."

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FIGURE CAPTIONS

Figure 1. A plot of the observed visibilities for the calibrator IRC+80052, shown with the observed statistical errors. For comparison we show the expected variation for a uniformly-bright circular disk having a diameter of 3.4 mas (expected for the calibrator) and scaled by the average response for the interferometer.

Figure 2. (a) A plot of the observed visibility for S Cep versus PA, compared to the expected variation for a uniformly-bright circular and a Gaussian. (b) A plot of the observed visibility for S Cep versus B_P, again compared to the same models. Note that the models behave differently than the observations of the star and indicate departures of the stellar surface brightness from circular symmetry.

Figure 3. The derived Gaussian FWHM for S Cep as a function of PA (♦), shown compared to an elliptically-shaped star (the dashed line). The field is 10 mas on a side with tic marks indicated for each 1 mas. North is to the right and east is up in the figure.

Figure 4. (a) A plot of the observed visibility for S Cep versus PA. (b) A plot of the observed visibility for S Cep versus B_P. In both panels the model elliptical Gaussian brightness distribution is shown for comparison.

Figure 5. (a) A plot of V versus PA for SS Cep. (b) A plot of V versus B_P for SS Cep. A circularly-symmetric Gaussian model is shown form comparison in both panels.